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A Performance Evaluation of Contention Resolution and Resource Allocation in Optical Packet Switched Network Scenarios

PROYECTO DE FIN DE CARRERA

PRESENTADO COMO REQUISITO PARCIAL PARA OBTENER
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POR

Javier Mozo Olea

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Instituto Tecnológico y de Estudios Superiores de Monterrey
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Los miembros del comité de evaluación del proyecto del alumno **Javier Mozo Olea** recomendamos que el presente sea aceptado como Proyecto de Fin de Carrera, requisito parcial para la obtención del grado académico de

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A Performance Evaluation of Contention Resolution and Resource Allocation in Optical Packet Switched Network Scenarios

by

Javier Mozo Olea

Abstract

Contention resolution represents a challenge considered when implementing resource allocation over optical packet switching. Analytical models are proposed to optimize the behavior of different architectures and networks in terms of contention resolution and resource allocation. Asymmetries in the network traffic distribution due to the network topology induce different dimensioning results, thus different topologies are studied to quantify the required number of links and fiber delay lines. Afterwards, two contention resolution strategies are introduced to quantify the impact on the number of converters and fiber delay lines over an optical packet switching architecture. Finally, a matrix model is defined to analyze blocking situations over an optical packet switching architecture, this model seems to be very powerful to improve the efficiency of the system regarding blocking situations. Simulation results show that the proposed strategies can be utilized to improve the performance of the utilized optical packet switching architectures in terms of resource allocation.

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Chapter 1

Introduction

In recent years, the growth of the traffic on the Internet and the fast advance of optical technologies have driven the evolution of Internet architecture. Data traffic has increasingly dominated the requirements for bandwidth over the networks, generating a shift from voice-optimized networking to IP-centric networking. At the same time, Wavelength-Division Multiplexing (WDM) technology has been widely deployed to meet this growing demand for bandwidth, resulting in an attractive platform to exploit the bandwidth potential of optical fiber links.[1]

The concept of Optical Packet Switching (OPS), which seeks to replace traditional electronic switching functions by optical ones, emerged as an alternative to coarser-grained optical switching. It holds the promise of almost arbitrarily fine transmission and a highly reconfigurable, flexible and bandwidth-efficient optical layer [2, 3, 4]. However, it faces significant challenges related to practical, scalable and cost-effective implementations of optical packet-level parsing and buffering [5]. There is a wide range of research opportunities combining experience from both networking and optical engineering.

Two main different functional layers are differentiated for this next-generation Internet (NGI): the Internet Protocol (IP) layer and the optical WDM layer. The IP layer concerns about the scalability of electronic routers to match the increasing transmission capacity of WDM architectures; the optical WDM layer is intended to combine this new IP routers with WDM transmission and switching systems, in order to provide a worldwide networking infrastructure for former and emerging IP-centric services.[1]

There is a further differentiation regarding the operating of OPS networks related to time: In a synchronous network, time is divided in slots and all packets are considered to have the same size. It is the responsibility of the input interface to synchronize arriving packets, aligning them with the time slots. These switches are easier to build and operate, hence they have received more attention from the OPS research community [6]. On the other hand, in an asynchronous network, packets are of variable size, and operations may take place at any point of time with no need to align the packets at the input of the architecture[7].

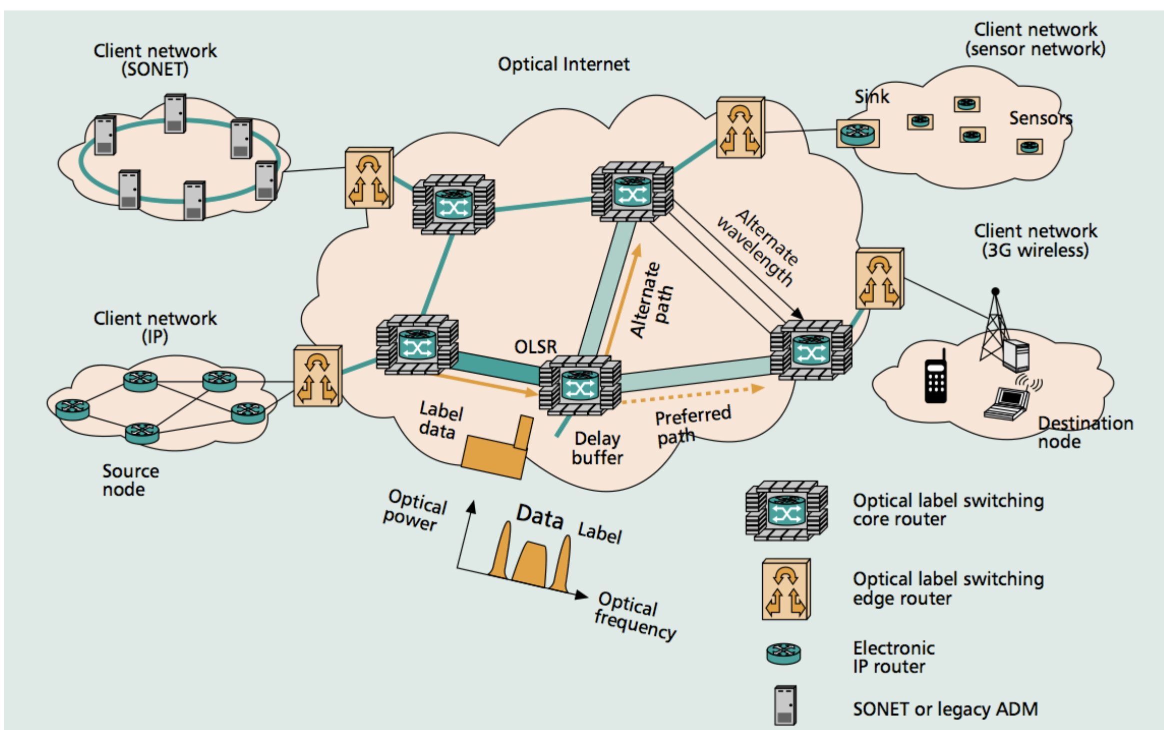


Figure 1.1: The Next Generation Internet.

An architecture proposal for the NGI is shown at Fig. 1.1 from [1]: this schematic corresponds to an Optical Label Switching (OLS) network, which intends to support interoperability between circuit, burst and packet switching. However, it shows the main OPS concepts related to this work: Packet routing through preferred and alternate paths is related to Multi-Path Routing (MPR) and Working-Protection routing schemes intended to avoid failures or attacks, information contained in different frequencies is on scope of WDM by means of wavelength converters, and delay buffers are utilized for solving blocking situations in OPS architectures.

This dissertation is focused on the optical WDM layer, by implementing WDM architectures over OPS synchronous networks.

1.1 Problem Statement

There are different problems related to the operating of optical packet switching architectures over the optical WDM layer, such as: *resource allocation*, *blocking situations*, *packet dropping*, and *computing complexity*.

Resource allocation. Resource allocation in the context of this thesis refers to the implementation of an strategy that permits to deploy the fewer resources as possible while offering an acceptable performance in terms of packet loss probability and efficiency. Different resources are involved in the analyzed OPS architectures: packets are buffered by means of Fiber Delay Lines (FDLs) and converted to other wavelengths by means of Tunable Wavelength Converters (TWCs). However, the utilization of these resources is limited to the number of TWCs and FDLs present in each architecture, which is limited by the cost and physical feasibility of the system; MPR requires higher utilization of resources than Single-Path Routing (SPR) techniques, since packets at each node may be sent through different routes, thus increasing the traffic of those alternative routes. Link dimensioning is also directly related to resource allocation, since it refers to the number of fibers present between two nodes of the network.

Blocking situations. Blocking situations refer to the cases where two packets attempt to utilize the same outlet of an architecture over the same wavelength. These cases are solved by means of different techniques: Packet buffering, wavelength conversion or MPR are some of those. All of these techniques are related to resource allocation in terms of buffers, converters and fibers.

Packet dropping. There are cases in which there is no feasible way to solve a blocking situation due to the unavailability of the link or the absence of utilizable resources. When this occurs, the packet is dropped. Packet dropping probability is obtained dividing the amount of dropped packets by the total number of packets injected, and is a parameter of critical importance in the design of an architecture.

Computing complexity. Computing complexity relates to the calculations required by the system in order to treat the upcoming packets entirely; that is, determine which output or resource to utilize, or when to drop a packet. This operating involves consultations on links and resources, attempting to know if they are utilizable or occupied. The objective is to perform these calculations in the most efficient way.

1.2 Objective

The objective of this work is to evaluate the performance of different OPS architectures in terms of the above depicted framework. A simulation tool implemented in the programming language C++ was used, and different strategies and resources were deployed depending on the requirements. Through the analysis of the results obtained from the simulations, it is possible to study the costs associated with the utilization of resources and the performance of the system in terms of packet loss probabilities. Finally, attempting to optimize the computing complexity of a single-switch architecture, and to reduce its blocking probability, a matrix method is introduced to implement additional considerations for allocating packets.

1.3 Thesis Organization

During the research, three articles were produced [8, 9, 10]. The present dissertation is composed of those, with the opportune adaptations and modifications to the present format: In the second chapter, the network dimensioning results and methods introduced in [8] are developed. The third chapter refers to the contention-resolution strategies depicted in [9]. The fourth chapter introduces the matrix model developed in [10]. The work is concluded with the fifth chapter, where conclusions and future work guidelines are given.

Chapter 2

Transparent Optical Network Dimensioning for Self-Organizing Routing

While transparent optical networks become more and more popular as the basis of the Next Generation Internet (NGI) infrastructure, such networks raise many security issues, which do not exist in traditional optoelectronic networks. The existing protection schemes, which rely heavily on fault detection with the use of network monitoring performed by optoelectronic conversion at the switching nodes, is not sufficient to provide security assurance for all optical networks that lack the massive use of optoelectronic monitoring and require timely protection from malicious sabotage as well as inadvertent faults. In order to increase the security of future networks, they will need to use reactive mechanisms and self-organize through multipath routing (MPR) to protect themselves from potential failures caused by malicious new attacks and ordinary reliability problems. In this chapter a method is proposed for network dimensioning when self-organizing routing as MPR is used as an instinct immediate network reaction to failures and attacks in transparent networks.

2.1 Introduction

Transparent optical packet switching (TOPS) networks are becoming more and more attractive due to their ability to reduce power consumption and total cost, this cost reduction is obtained through the use of a lower number of transponders, TOPS networks can also avoid the bottleneck of optoelectronic conversion and switching at each node. However, transparency raises many security vulnerabilities as well as reliability issues that do not exist in traditional optoelectronic networks [11, 12]. In WDM systems, multiple optical signals co-propagate in fiber and optical components, possibly affecting each other directly or indirectly. Then, the quality of a signal is sometimes dependent on or degraded by other signals. Moreover, in a transparent network, it is desired that signals are not regenerated between source and destination nodes unless it is absolutely necessary [13]. It has been discussed in [14] how signals can be maliciously designed to pass through transparent components, causing undesirable effects at remote components and degrading other signals passing through those components. Security and reliability issues are of utmost importance in transparent optical networks given the extremely large fiber throughput. Fast and successful reaction and restoration mechanisms performed by failure management can prevent loss of large amounts of critical data, which can cause severe service disruption. In this chapter, MPR is proposed as a method for network dimensioning for self-organizing routing when MPR is used as an instinct immediate network reaction to failures and attacks in transparent networks. The utilization of this method is proposed to validate self-organizing routing in TOPS networks to deal with failure management. The possibilities of developing such a network architecture and its implications on network security are investigated.

Dimensioning on TOPS Networks must deal with issues such as the number and allocation of fibers, buffer size as number of delay lines, wavelength converters, number of wavelengths and protection capacity that guarantee availability while minimizing the allocated spare capacity. Previous work focuses on single-node dimensioning [15, 16] on the number of fibers and buffers. In [17] Danielsen et al., address the idea of increasing the number of wavelengths in order to have a bufferless TOPS network, however a bufferless network can only offer a maximum fiber utilization of 0.28, which is too low and a large amount of bandwidth is wasted. There are no studies reported about dimensioning TOPS networks taking into account the idea of MPR to distribute the traffic among nodes and alleviate the amount of traffic loss when a link with several fibers are lost by failure, cuts, or attacks.

To demonstrate the availability protection scheme it is assumed that only one link failure or cut occurs in the network at a time. Link failure or cut means that all fibers into that bidirectional link are deactivated. The network is dimensioned through the use of a Monte Carlo network simulator by using three routing schemes. The first strategy is the MPR [18, 19, 20]. The second is named working-protection paths with shortest distance (WP-SD). The third is the working-protection paths with least number of hops (WP-LNH). These last two routing strategies use a node disjoint working path and a backup path assigning priority to shortest paths for WP-SD and to least number of hops paths for WP-LNH. The strategy proposed for MPR dimensioning attempts to provision connections with guaranteed availability while minimizing the allocated spare capacity. The connection availability estimation uses the matrix-based approach of multi-path information.

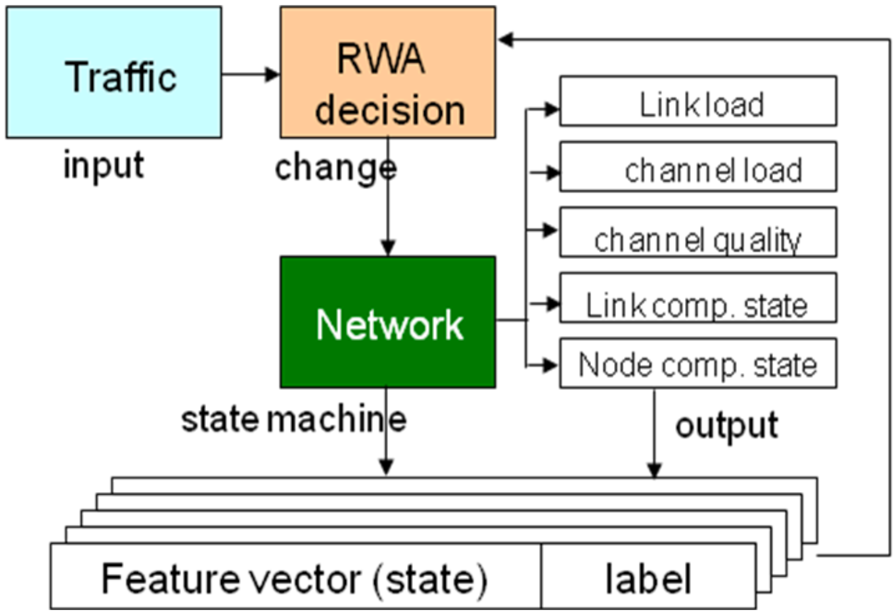
Self-organizing routing could possibly be applied to develop a highly scalable and robust failure management scheme. In self-organizing systems, local interactions between individual components achieve global properties. The self-organized routing strategy is based on two approaches: i) the use of MPR as an instinct immediate network reaction to failures and attacks in transparent networks [11, 12, 18, 19, 20] and ii) after the nodes transmit the data and causes of failure are classified, better self organized autonomous decisions can be made based on changing routing output priorities of MPR to reach destination. In this chapter a method is proposed for network dimensioning for self-organizing routing MPR, and network resources are compared with other protection schemes.

2.2 Self-organization

A multitude of complex self-organizing systems can be found in many areas of life and science. In nature, ants lay trails of pheromones between various food sources to achieve an efficient network of shortest paths, birds organize themselves into flocks, also, bees fly and look for food in well-structured swarms. In human brains, neurons self-organize and perform functions without any central conductor. Self-organization arises in many other branches of science, such as economy, population dynamics, psychology, mathematics (evolutionary computation), computing, robotics and telecommunications. The interconnection of Web pages created by millions of uncoordinated Web publishers [21] is arguably one of the most interesting examples of self-organization to the engineering community. Although self-organizing concepts have not yet been fully exploited in the design and functioning of telecommunication networks, the application of these concepts to various areas in communications is currently intensively being researched. Examples include applications in peer-to-peer networks [18], as well as ad hoc and cellular wireless networks [22, 23, 24]. However, these concepts have not yet been explored in the context of the dimensioning of transparent optical networks.

2.3 Related Work

Network security countermeasures are categorized into three types of practices: $prevention$, $detection$ and $reaction$. Since attacks are achieved via physical layer impairments, limiting the physical layer vulnerabilities is of common interest in both reliability and security research [25]. In transparent optical networks, prevention schemes that aim to reduce vulnerabilities include network design, component design, provisioning, and operational regulations, etc. In general, two approaches exist to assure reliable optical channels in the presence of physical layer impairments: the routing constrained by estimated physical layer impairments and the network architecture design to guarantee the service quality in every possible case in the given network and traffic demand [11, 12].



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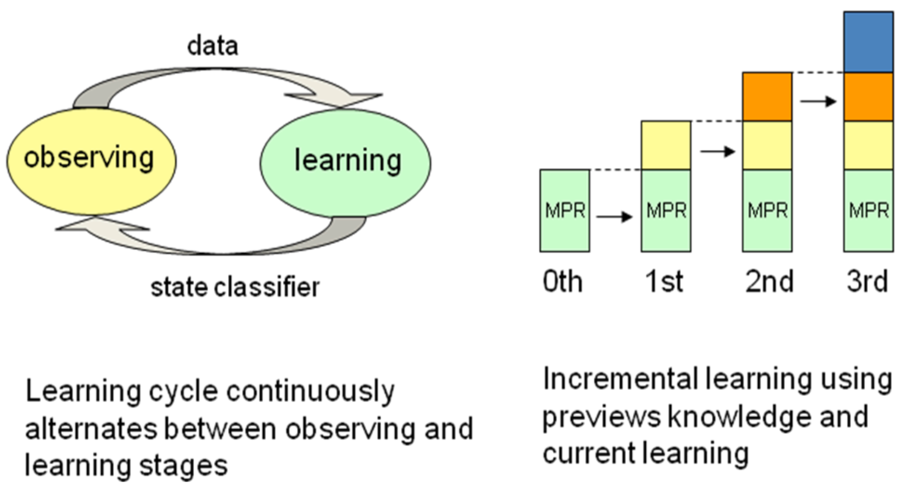


(b)

Figure 2.1: Conceptual diagrams. (a) Self-organizing mechanism: The network is modeled as a state machine. The approximate functional relationship between states and outputs of the state machine is learned, and then used to make routing decisions. (b) Learning cycle continuously alternates between observing and learning stages and incremental learning using current and previous data observing and learning stages.

The purpose of self-organization is that if a network experiences significant physical layer impairment problems in certain network conditions, it learns them, and then tries to keep away from any of such conditions or unforeseen but similar conditions which are expected to produce similar or worse performance. For example, instead of blindly using the first-fit route, it is proposed to use a flexible multi-path routing (MPR) scheme, which chooses the safest path, satisfying the packet or the burst of packets. It is well known that multi-path routing has many benefits, such as decreasing the number of components in an all-optical network, decreasing the use of optical memory (fiber delay lines) at the routers, decreasing the use of wavelength converters, provides a quick way to solve contention of packets, faults, and attacks using an alternate routing [11, 12, 18, 19, 20, 21]. Multi-path routing uses a packet forwarding output link table with several output link options ordered by priority. Initially this forwarding table may be created using the k-shortest paths based on the minimum hop routing. For example in case of a packet conflict, one of the packets will be forwarded through the output link with the best priority and the second packet can be forwarded through the output link with second priority in case the node does not have other contention resolution mechanism as optical memory and wavelength conversion. The node's forwarding routing tables can be continuously self-organizing based on the conditions of the network of the state machine and using routing algorithms that update the forwarding tables based on the different faults or attacks the network may suffer. The key difference from previous work is that such intelligence is obtained without human intervention or without instantaneous detailed knowledge of the network component subsystem, apart from its ability to self-organize autonomously as the network changes. A supervised machine learning approach is used for pattern classification to support this approach. If we make the analogy to the human immunization system's primary defense mechanism, Multi-path routing will act as the primary defense mechanism reacting timely to network problems and evolving based on the network information. Basically, the use of MPR is proposed as an instinct immediate network reaction to failures and attacks in transparent networks and after the nodes transmit the data and causes of failure are classified, better routing decision can be used based on changing routing output priorities of MPR to reach destination. In this case routes of MPR will be continually updated based on the state of the network. Here, network is defined as a $statemachine$, where the current $state$ of a network is defined as the current set of wavelength usage status on each link in the network and supplemental important information as the state of node and link components. Since intelligence is distributed, every node has to send information to all other nodes in the network about the state of the wavelengths, state of the fibers, and state of the links components and state of the nodes components. It is important to mention that it is assumed that a link comprises several transmission fibers and in the same way a fiber comprises several wavelengths. The goal is to address this problem with autonomous adaptation against new vulnerabilities and the effective recognition of risks. Monitoring and detection methods in AONs are discussed in [26]. Failure location algorithms which provide a framework to locate faults and attacks in AONs also exist [27, 28, 29].

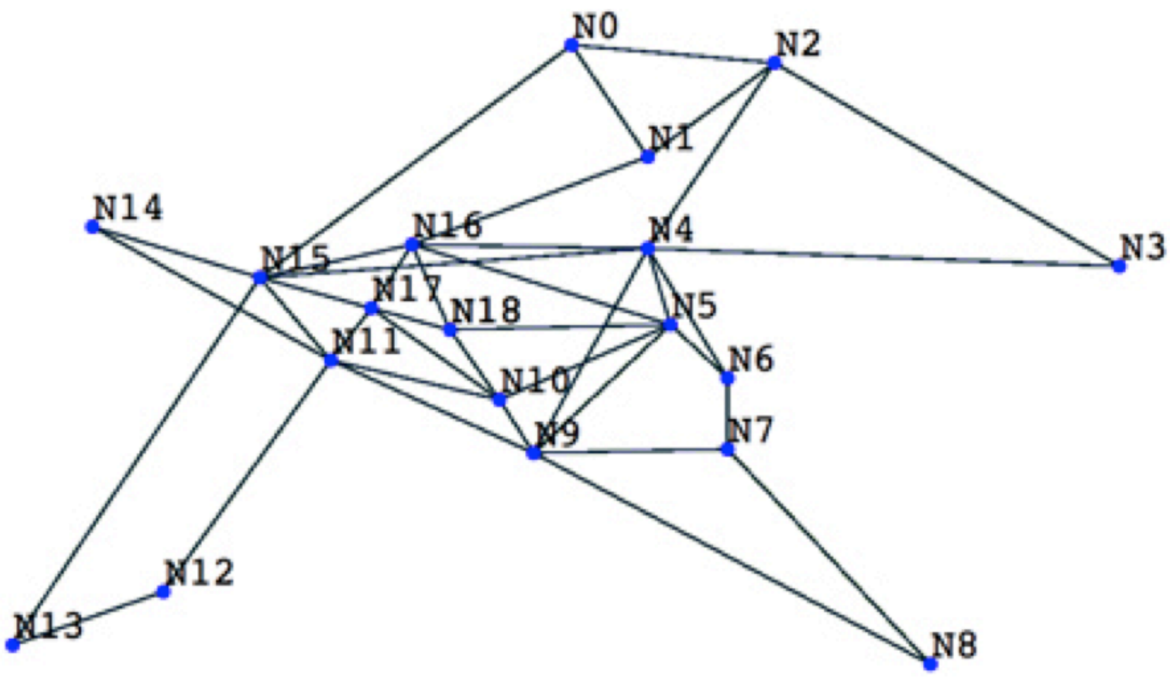


Figure 2.2: European topology.

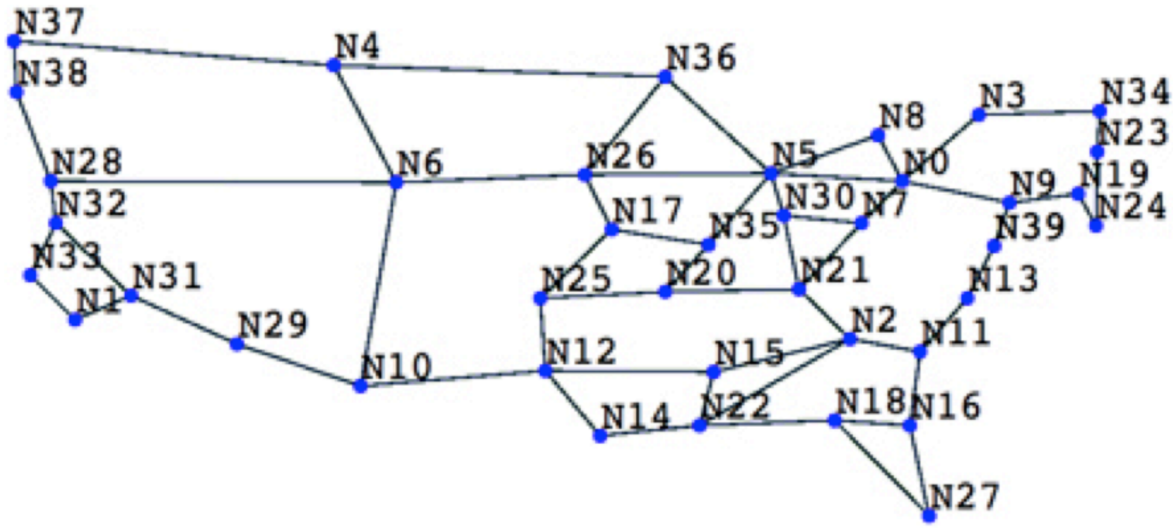


Figure 2.3: USA topology.

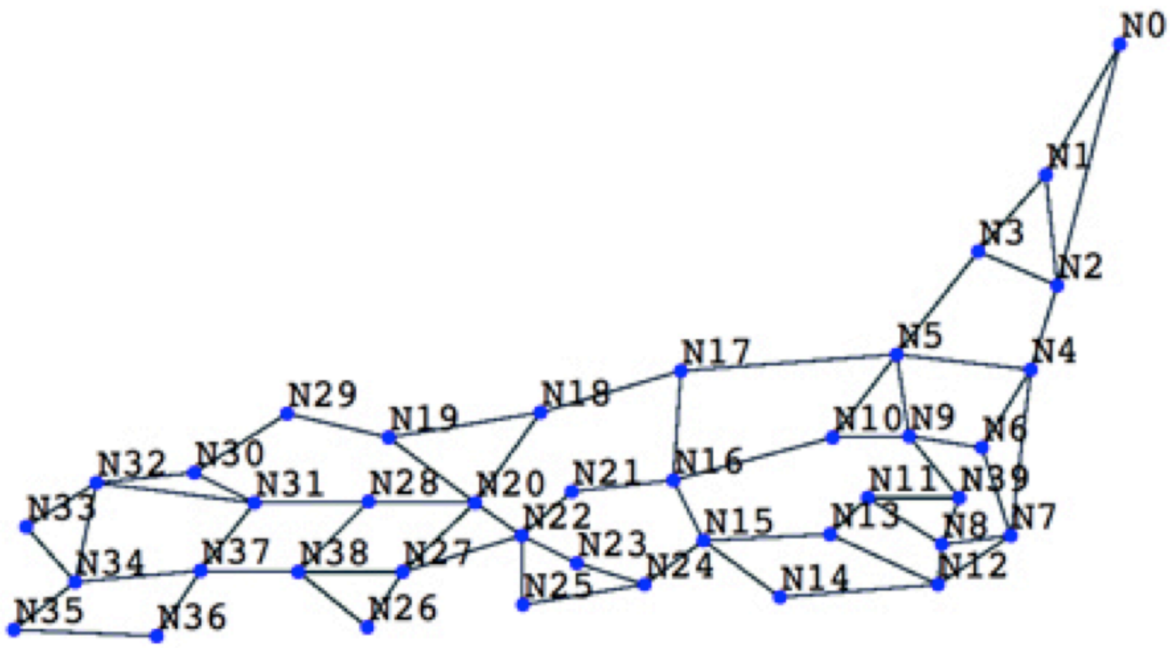


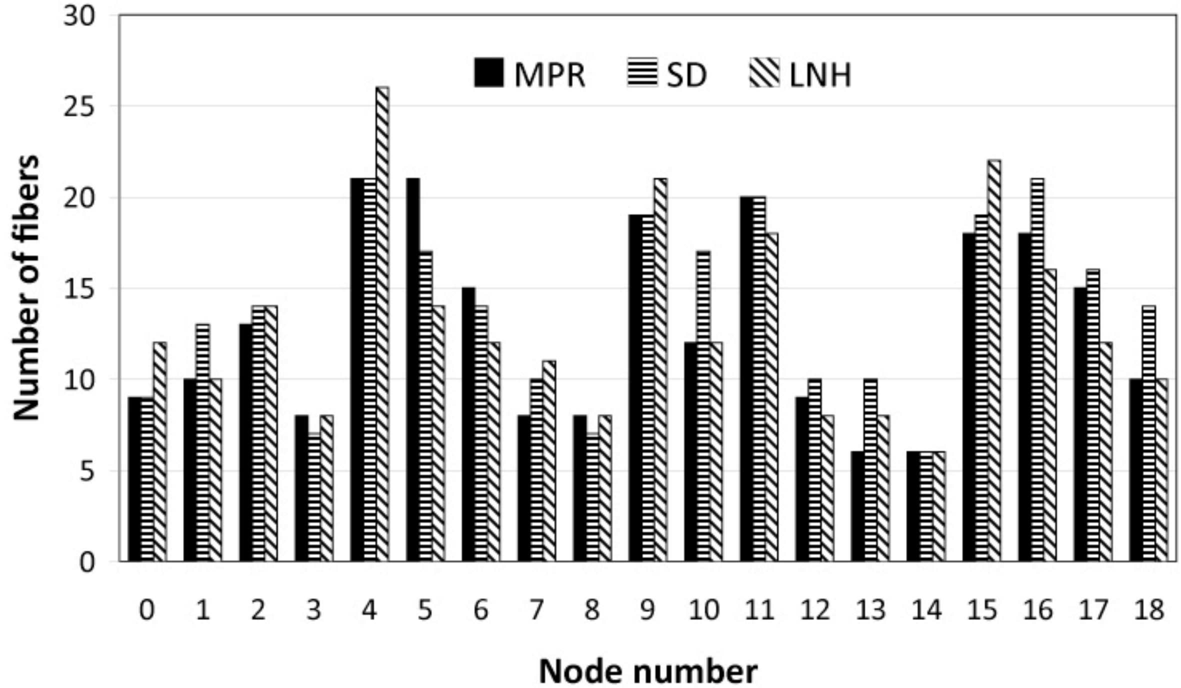
Figure 2.4: Japanese topology.

2.4 Results

Since we are interested on the number of delay lines and the number of fibers per link required for the three routing schemes WP-SD, WP-LNH and MPR, a router and network dimensioning algorithm was applied, which consists of increasing the buffer depth by one unit every time a packet is lost in a specific outlet. It is important to mention that the router architecture used in the simulations to dimension the delay lines is the one with output optical buffers [30]. Also, when the number of delay lines reaches the limit, the number of fibers for that specific link is increased. At the beginning of the simulation, the buffers depth is 0 and the maximum buffer depth allowed during the network dimensioning period is 3. For buffer dimensioning for MPR, the simulator first tries to solve blocking by storing the packet at the available buffers and with the use of wavelength conversion, if blocking cannot be solved the simulator increases the buffer depth of the outlet with the highest priority. In a similar way if the number of buffers reaches the maximum value and a fiber is required, then the simulator increases the number of fibers in the output link with the highest priority. Fiber cuts were introduced to the bidirectional fiber links and dimensioning was performed on the alternate second priority paths for all routing strategies. These cuts were introduced sequentially, cutting one link at a time and allowing the simulator to dimension the network until steady-state was reached.

Results of network dimensioning using the topologies of Europe (Fig. 2.2), USA (Fig. 2.3), and Japan (Fig. 2.4) are compared: The topologies have 19, 40, and 40 nodes respectively. Figures 2.5(a) and 2.5(b) show results for the European topology in terms of fibers per node, and number of fiber delay lines using the three routing dimensioning schemes. It is shown that the number of fibers utilized in the network when MPR is used for dimensioning is fairly similar to the one obtained by WP-SD and WP-LNH. It can also be observed that MPR uses a higher number of delay lines. In Fig. 2.6 we can observe that the use of MPR results in a saving in number of fibers used, approximately a 20% reduction with respect to both, WP-SD and WP-LNH, while the number of delay lines increases in about 16% with respect to WP-SD. One major advantage of MPR is that as soon as a disruption appears at a pair of nodes, the packets will be instantaneously assigned to the second priority route, while in the cases of WP-SD and WP-LNH a message of link disruption needs to be sent to the source nodes to assign the packets to the protection route. Figures 2.7(a) and 2.7(b) show results for the Japanese topology. We observe that MPR also decreases the number of fibers used in the network in about 23% with respect to the other two schemes, with an increment in the number of delay lines of approximately 13% compared to both WP-SD and WP-LNH.

The number of clock cycles (or time slots) per link cut used for the optical buffers, fibers, dimensioning and for the transient period of the simulation were 10,000 which is enough for the network dimensioning and for the transient period to died out. The simulation clock cycles depend on the number of links in the network. For instance, to compute the statistics presented in the results of the European network data was collected for 450,000 clock cycles during the steady-state period. To be sure that the simulation was in steady state at the time the computation started, the mean number of packets injected into the network per time slot (injection throughput) with the mean number of packets going out of the network per time slot (absorption throughput) plus the mean number of packets lost in the network per time slot (lost throughput) after the transient period were compared. For every probability of packet injection, a small difference of the order of 10^{-2} was obtained between the injection throughput and the sum of absorption throughput and lost throughput.



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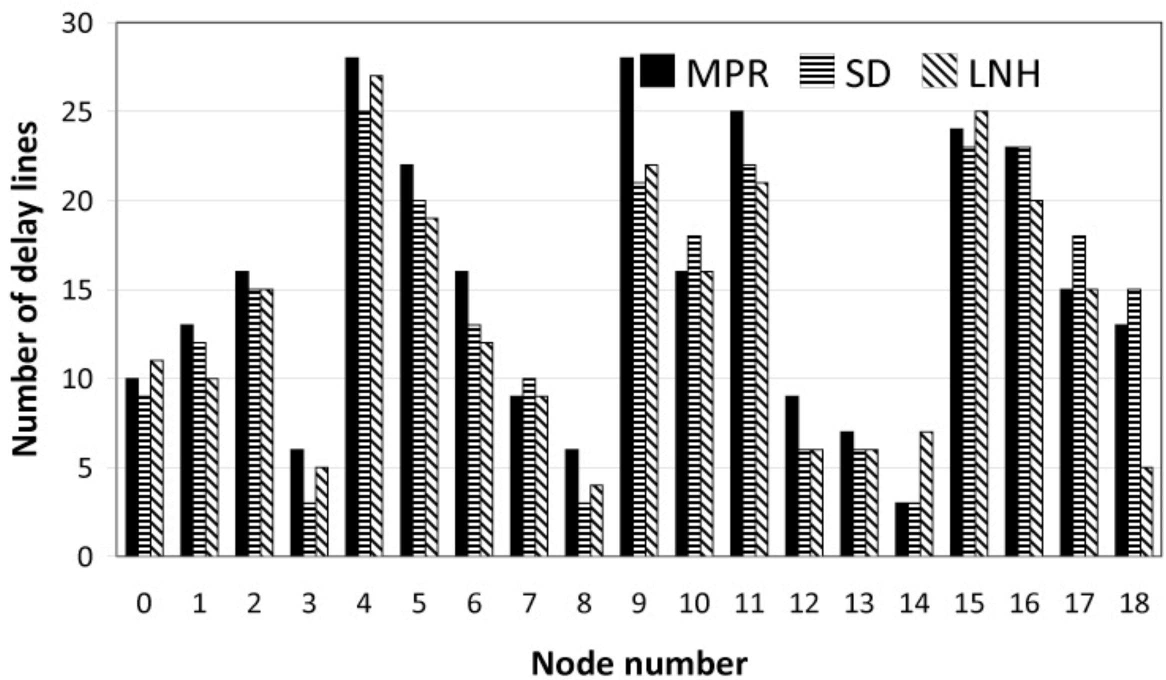
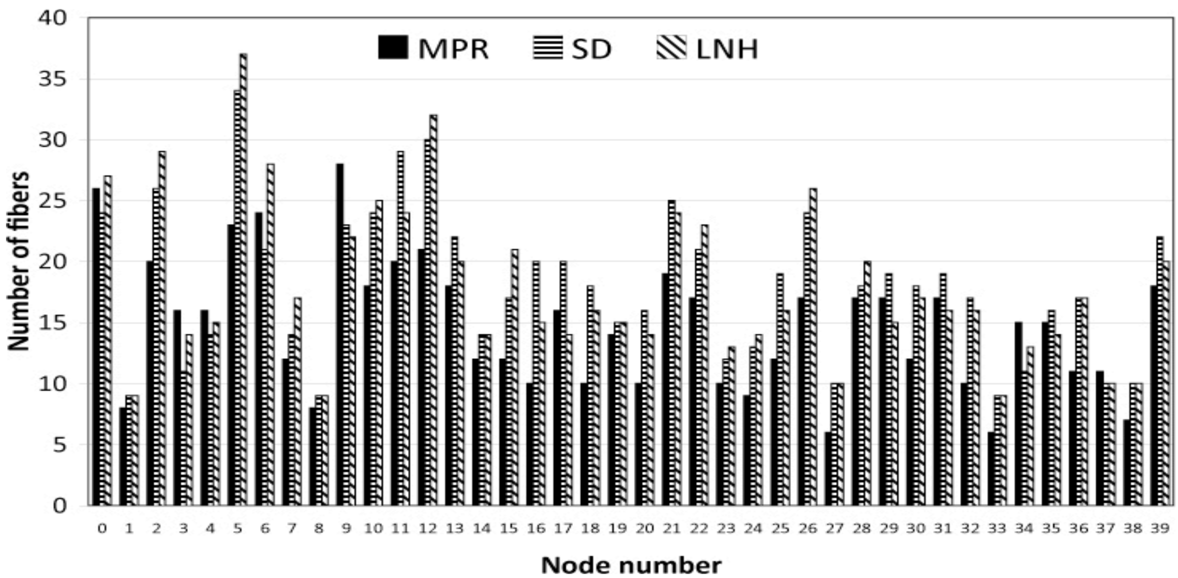


(b)

Figure 2.5: Dimensioning results for European topology. (a) Number of fibers per node. (b) Number of delay lines per node.



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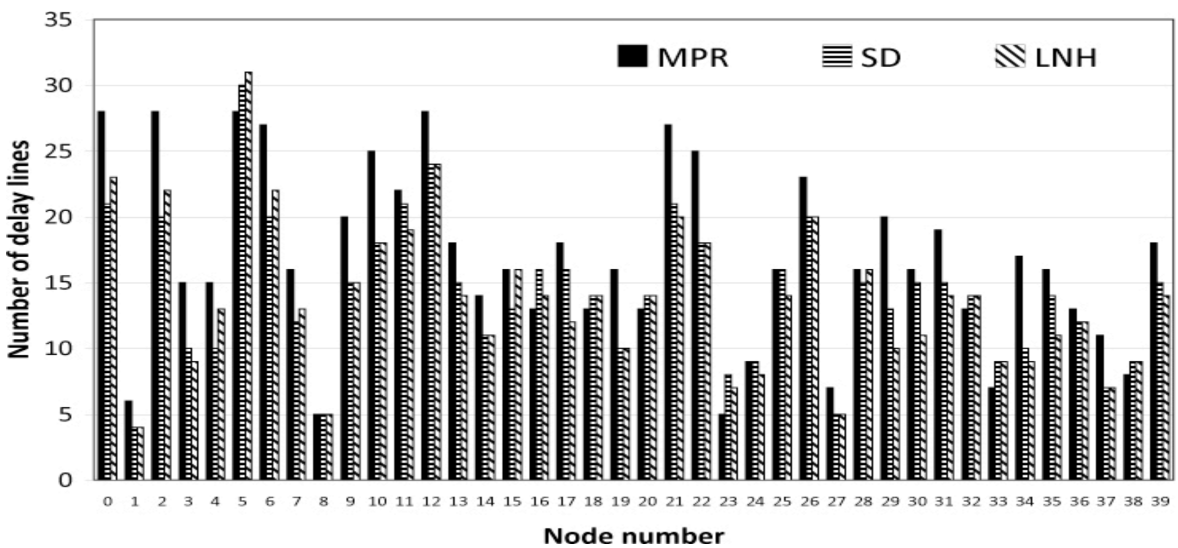
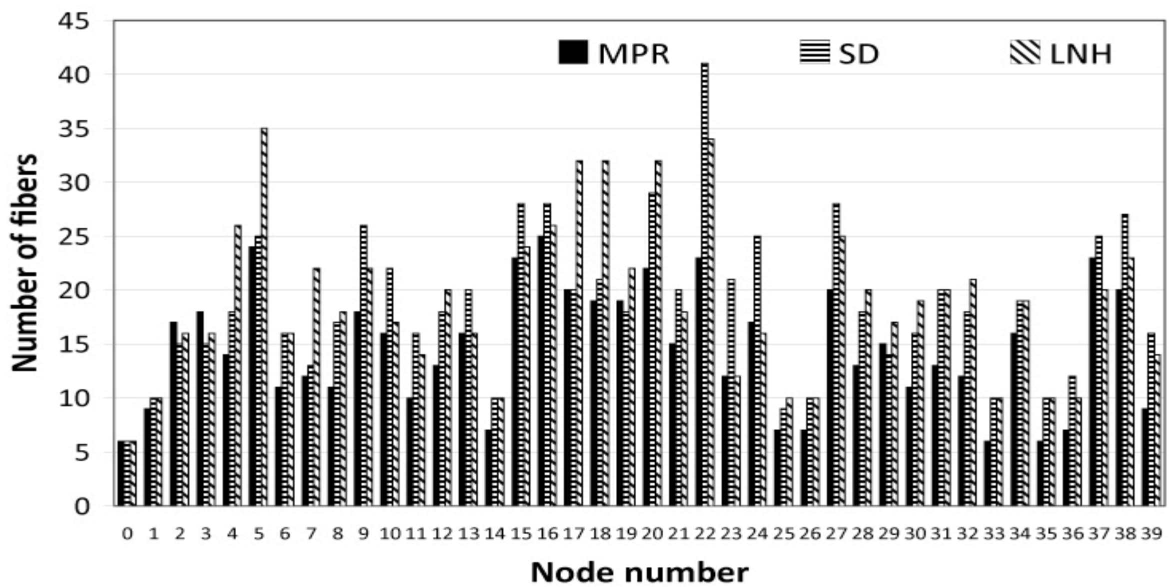


(b)

Figure 2.6: Dimensioning results for USA topology. (a) Number of fibers per node. (b) Number of delay lines per node.



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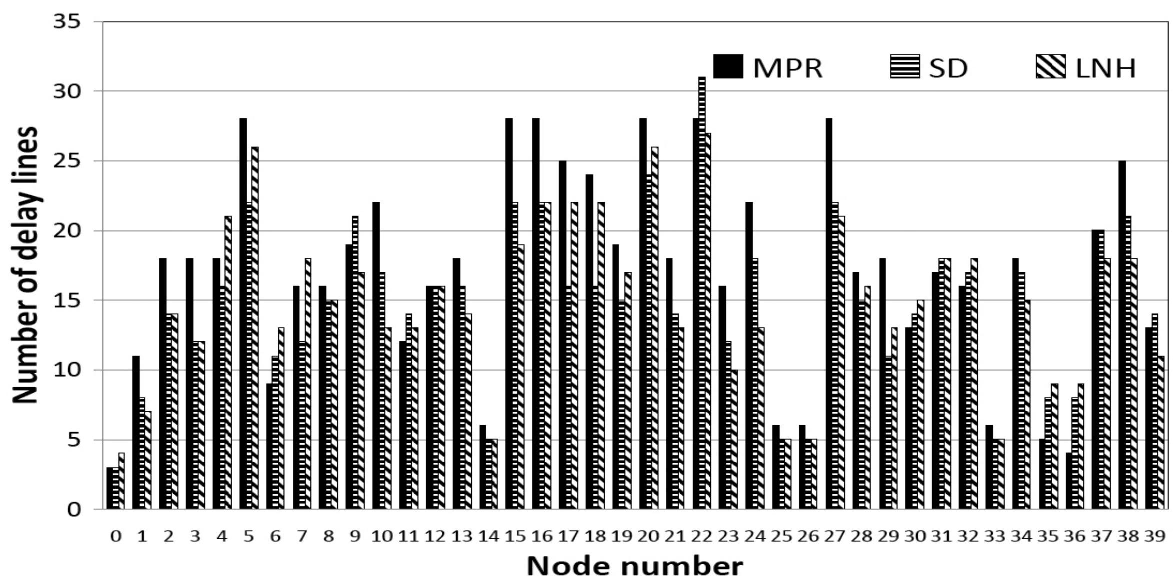


(b)

Figure 2.7: Dimensioning results for Japanese topology. (a) Number of fibers per node. (b) Number of delay lines per node.

2.5 Conclusions

It is shown that network dimensioning using MPR offers advantages in the reduction of number of fibers used in the network when compared to WP-SD and WP-LNH. This represents a major advantage since a lower number of fibers implies that all components needed in a fiber link between two nodes are reduced as well, such as optical amplifiers, demultiplexors, dispersion compensators, transmitters and detectors, etc. On the other hand, MPR has the disadvantage of an increase in the number of delay lines, however the cost advantage of reducing the number of fibers used in the network offsets by far the cost increase of a higher number of delay lines, which in any case is not significantly higher. Moreover, MPR has the added advantage of responding instantly when link disruptions appear, by assigning packets to the second priority routes at the nodes where the disruption occurred, without having to refer to the source nodes as in other schemes.

Chapter 3

Resource allocation for contention-resolution strategies in OPS

All-Optical Networks are believed to be the basis of the Next Generation Internet (NGI) infrastructure. Contention resolution represents a challenge considered when implementing resource allocation. This chapter presents a performance evaluation for Optical Packet Switching (OPS), attempting to solve contention resolution applying resource allocation through two strategies: Minimum packet buffering ($minBuff$) and minimum conversions ($minConv$). An OPS architecture with a shared converter pool and output buffers is considered. It is shown that for a given dimensioning, an appropriate strategy may optimize the performance of the system in terms of packet loss probability.

3.1 Introduction

Transparent All-Optical Networks (AON) are intended to provide high-speed operation at network level, by not only avoiding the bottleneck of optoelectronic operations at each node but also reducing the use of transponders and power consumption in the network [31, 8]. Mainly two different architectures are considered to support the Next Generation Internet (NGI) infrastructure: Optical Burst Switching (OBS) and Optical Packet Switching (OPS) [32]. OBS aggregates user data at the edge of the network, grouping it into variable sized bursts [33] while OPS attempts to individually process data into fixed size packets [5]. The most common implementations on optical switching architectures are based on Wavelength Division Multiplexing (WDM), where one of the challenges is related to contention resolution to determine the procedure to assign resources to the packets: how a burst/packet must be stored by using Fiber Delay Lines (FDLs) or converted to other wavelength by means of Tuneable Wavelength Converters (TWCs).

Previous research with shared converter architectures is based on bufferless packet/burst switch modelling [34], blocking probabilities with buffered converters in OPS/OBS [35], and an analysis of some contention resolution strategies in OBS [36]. In contrast to that previous work, this chapter presents a performance evaluation over an optical packet switching architecture with a shared converter pool and output buffers considering two strategies to minimize either, the packet delay or the number of wavelength conversions. The remainder of this chapter is organized as follows: section 3.2 presents the switch architecture, its resources and key design and dimensioning parameters for contention resolution. Afterwards, section 3.3 describes contention resolution strategies and the model for performance evaluation. Section 3.4 shows the results of the impact of the number of converters and FDLs with the strategies considered. Finally, section 3.5 presents the conclusions of the study and further research topics.

3.2 Switch Description

The architecture of the optical switch analyzed is shown in Fig. 3.1: The demultiplexer (DMUX) separates the wavelengths $\lambda_1, \ldots, \lambda_n$, coming in a WDM signal. Then, the packets are processed attempting to avoid dropping of packets by making use of the resources as TWCs and FDLs. The router has the functions of packet dropping (absorption), adding (injection), wavelength switching (conversion), space switching and buffering.

There are several parameters involved in the performance of the different events above depicted:

Architecture: The architecture of all-optical routers is closely related to its physical realization, focusing on the switch complexity, buffer size and number of wavelengths. Different architecture models have been discussed for OPS [37]. For analyzing the performance of the mentioned schemes we used the one of the Fig. 3.1.

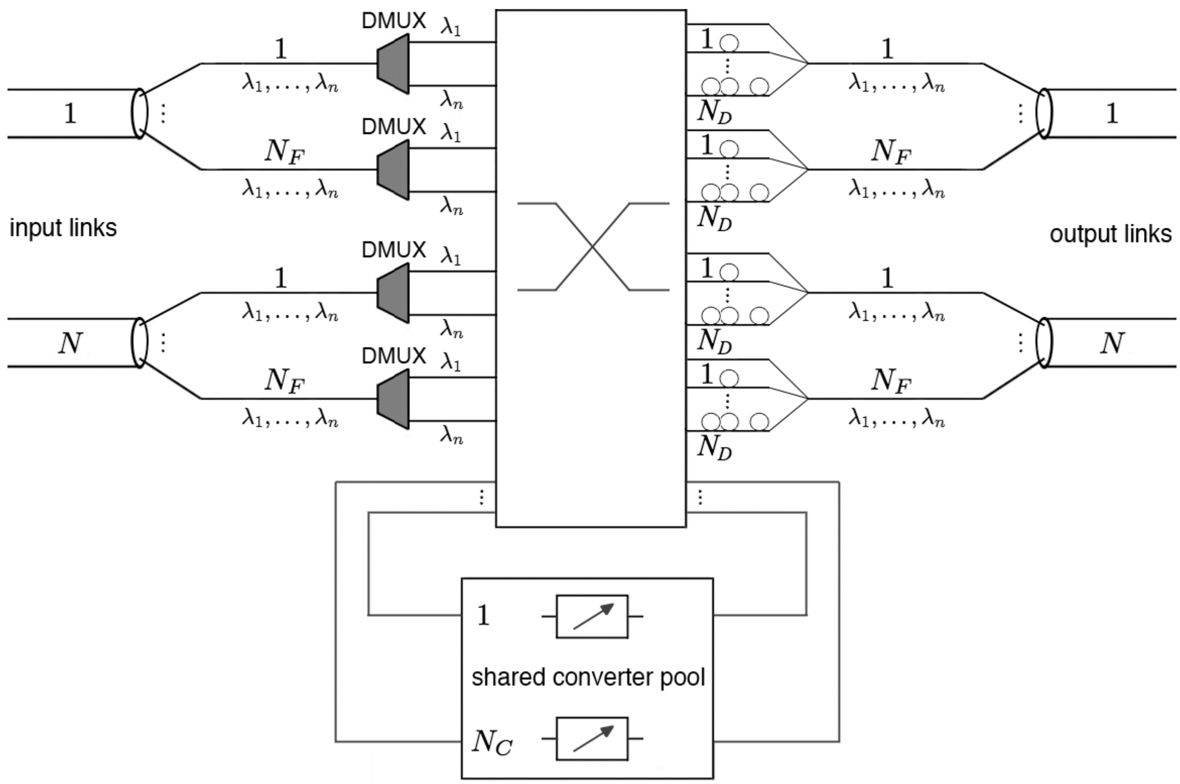


Figure 3.1: Analyzed OPS architecture.

TWCs and FDL buffers: Resources may provide, full or partial functioning, depending on its complexity related to the number of inputs, wavelengths and traffic load. The role of a converter pool is to share a given number of TWCs among the inputs, by providing converting capability within a limited conversion rate; TWCs are recognized as essential for reducing the complexity of switches. FDL buffers are placed at the outputs, intending to provide buffering in order to solve contention situations. Once a packet is stored in the buffers, it will be sent out immediately when it reaches the end at the FDL.

3.3 Design and Implementation

The purpose of contention resolution is to decide what to do when two packets need to use a resource (TWC or FDL) at the same time. An effective contention resolution strategy attempts to keep resources utilization low, allowing to save a number of them.

3.3.1 Probing Strategies: Minimum Buffering and Minimum Conversion

In a node where a Converter Pool and an FDL buffer are utilizable, both resources can be probed in different orders depending on how the contention resolution options are considered. There are four possible actions to perform when transferring a packet: a) Transmission on the original wavelength without buffering; is the preferred one when possible, since it does not imply the use of any resource; b) Transmission on the original wavelength after buffering; if possible, stores the packet in a FDL for a certain time, transmitting it once it pops out; c) Transmission after wavelength conversion without buffering; if possible, transmits the packet immediately by using one of the TWC; d) Transmission after wavelength conversion after buffering; is the least preferred, since it makes use of both resources; FDLs and TWCs. We considered two strategies: Minimum buffering ($minBuff$) and Minimum conversions ($minConv$); which perform as follows: $minConv$ intends to minimize the number of conversions by considering b) over c), and $minBuff$ attempts to minimize the packet delay by considering c) over b).

3.3.2 Model for Performance Evaluation

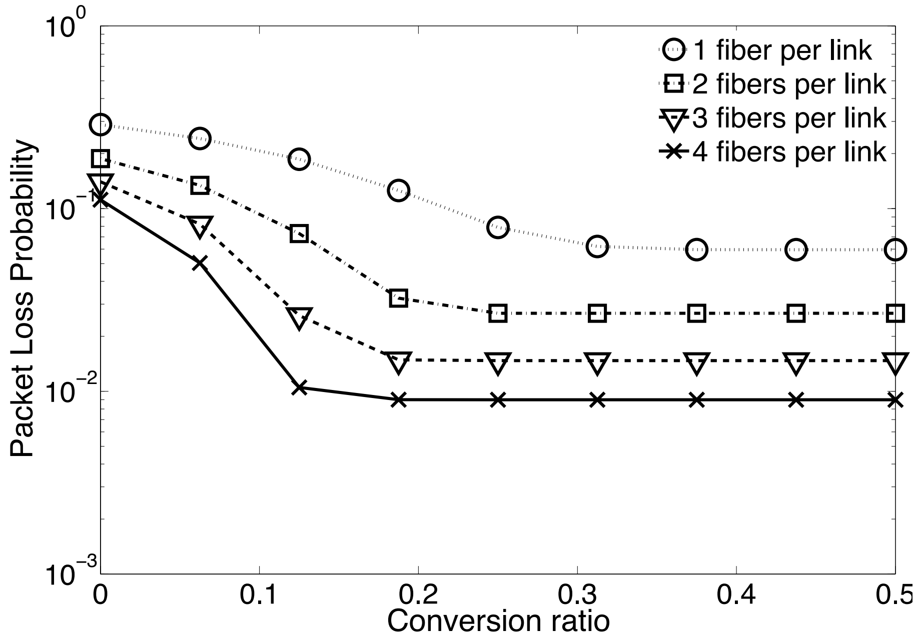
We created a simulation tool in C++, which runs 10^5 simulation clock cycles over an OPS synchronous switch model. Packets are uniformly distributed over the outlets and wavelengths. The node has N input and output links with N_F fibers per link, and n wavelength channels per fiber. The number of shared converters in the converter pool is given by N_C, and the conversion ratio is defined as $r_c = N_C/(N{\cdot}N_F{\cdot}n)$. Each output has an FDL buffer with N_D

fiber-delay lines.

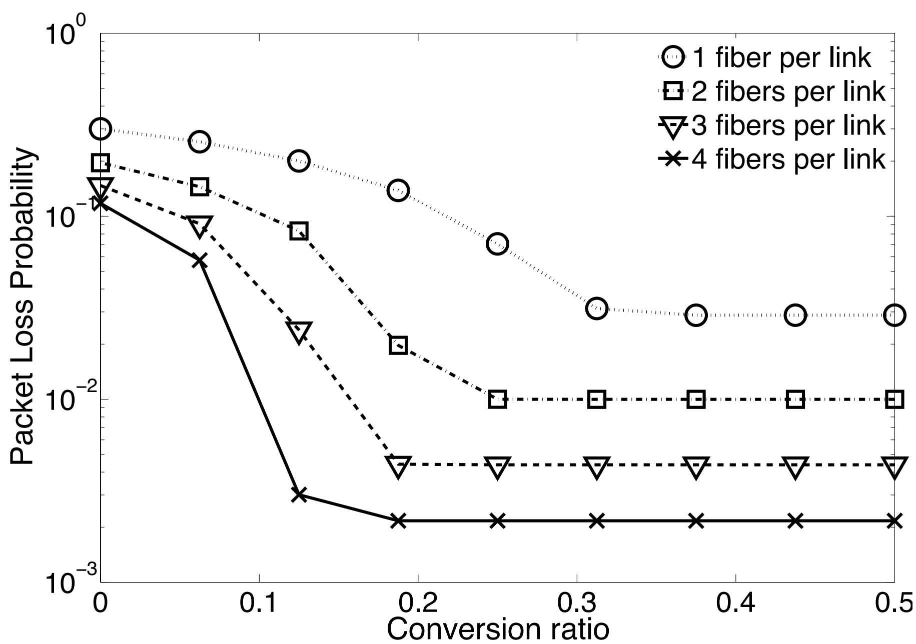
3.4 Performance Evaluation and Results

Packet loss probability vs. conversion ratio for different number of fibers per link is depicted in Fig. 3.2(a), where $n = N = 8$, traffic load was set at 0.8 and no FDLs were introduced. There is a lower boundary at which the packet loss probability does not improve further by adding more converters, which is reached at different points depending on the number of fibers per link. For the case of 1 fiber per link, it is reached at a point close to 0.3; which means that about 70% of the maximum number of converters could be saved without incurring in performance losses. The case of 4 fibers per link permits more saving; about 80% of the converters do not have influence on the loss ratio, and the loss probability for this point is much lower than for the cases with fewer fibers per link, due to the spatial multiplexing gain. As observed in Fig. 3.2(b), loss probability reaches lower values when considering a router with $N = 16$ outlets and with $n = 16$ wavelengths. This is due to the greater freedom when converting packet channels, since a larger wavelength bundle is available.

The following results are obtained for the model provided in Fig. 3.1 with $N = 8$ outlets, $n = 8$ wavelengths and $N_F = 2$ fibers per link. Traffic load is set to 0.8, excepting Fig. 3.3(b). Figure 3.3(a) shows results of the impact of FDLs over the packet loss probability for both strategies, with fixed conversion ratios at $r_c = 0.0625$ and $r_c = 0.25$. It is observable that the absence of FDL makes both strategies equal. When FDLs are introduced, a lower loss is obtained and differences between the strategies start to become apparent. $minConv$ permits lower loss probability than $minBuff$ when the conversion ratio is low $r_c = 0.0625$; this is due to its optimization on converter usage. When the number of converters is increased enough ($r_c = 0.25$), $minBuff$ performs better than $minConv$ because of its lower boundary, which is reached at a higher conversion ratio, but offering lower loss probability.

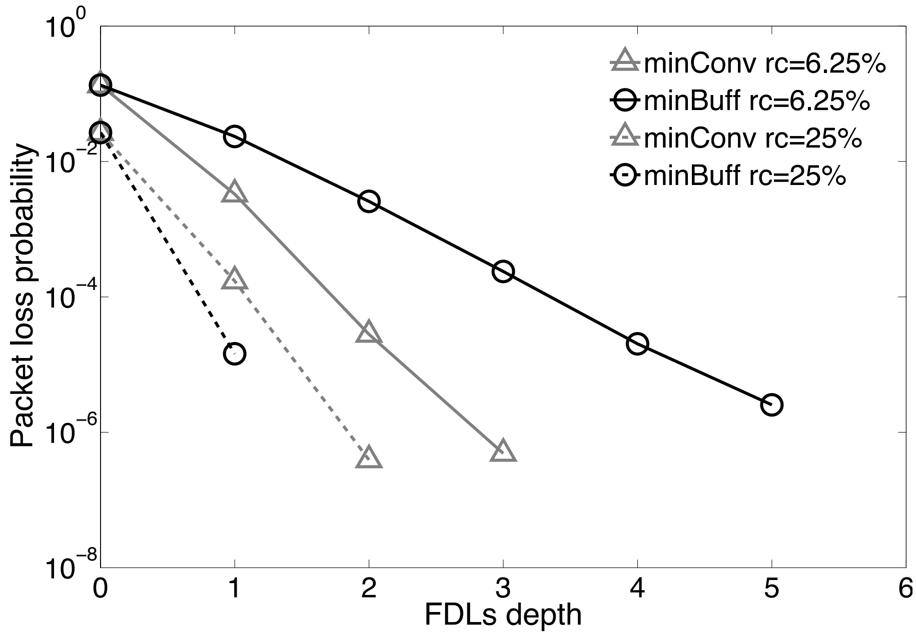


(a)

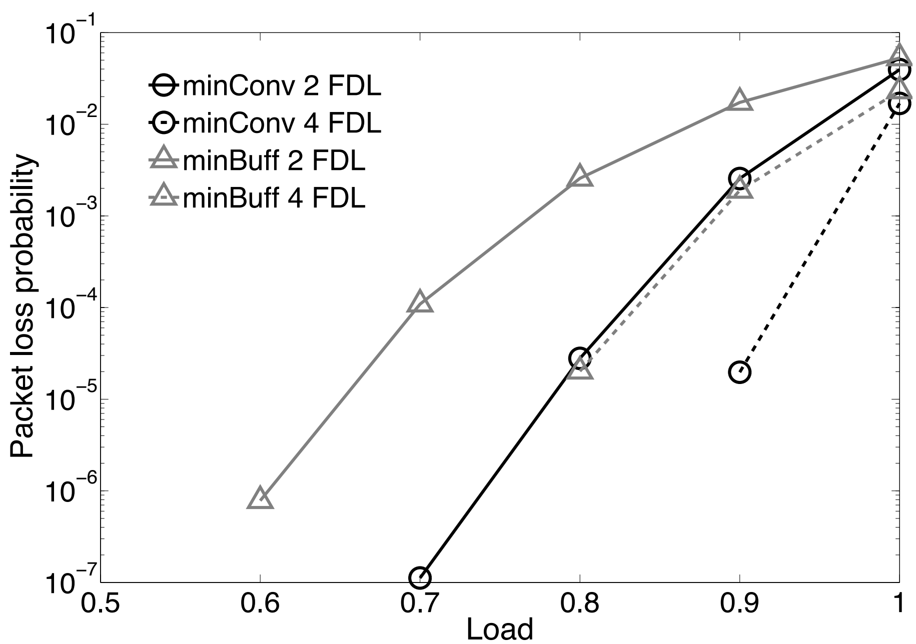


(b)

Figure 3.2: (a) Packet loss probability vs. conversion ratio $N = n = 8$. (b) Packet loss probability vs. conversion ratio $N = n = 16$.

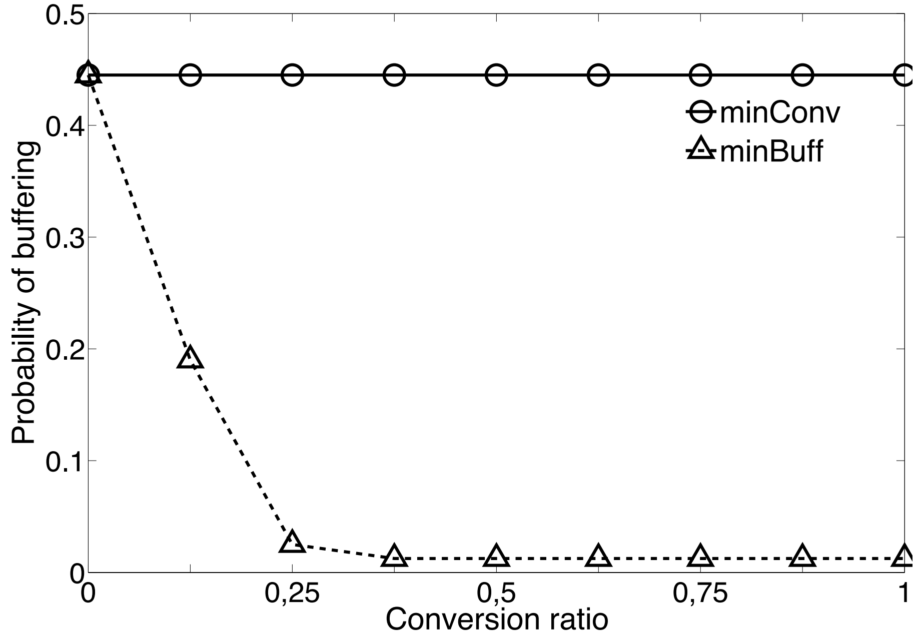


(a)

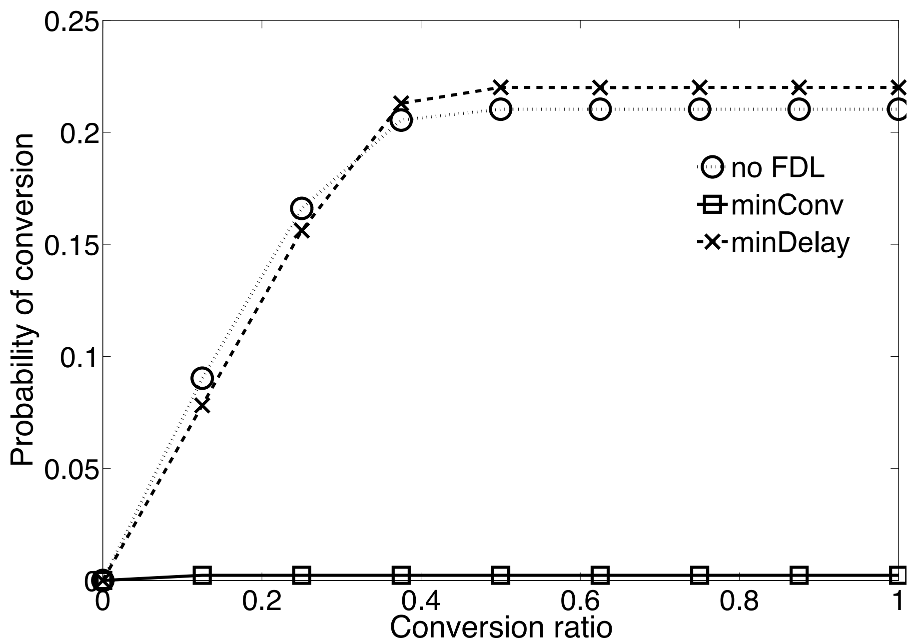


(b)

Figure 3.3: (a) Impact of FDL buffer depth and probing strategy for $r_c = 0.0625$ and $r_c = 0.25$. (b) Impact of load and probing strategy for different FDL buffers with $r_c = 0.0625$.



(a)



(b)

Figure 3.4: (a) Probability for buffering (4 FDLs). (b) Probability for conversion (4 FDLs).

The impact of load offered over the probing strategies for different FDL buffers is depicted at Fig. 3.3(b) with $r_c = 0.0625$. Packet loss probability becomes higher as load increases, due to the higher utilization of the resources; $minConv$ offers better performance than $minBuff$ for this conversion ratio. Furthermore, as more FDLs are utilizable, the performance improves in terms of loss ratio for both strategies.

Figure 3.4(a) depicts the probability of buffering a packet vs. conversion ratio for $N_D = 2$ fiber delay lines. For $minConv$, the probability of buffering remains the same for every conversion ratio; on the other hand, for $minBuff$, the buffering utilization lessens as the number of converters increases, since it considers transmission after wavelength conversion without buffering over transmission on the original wavelength after buffering.
The probability of conversion vs. the conversion ratio is shown at Fig. 3.4(b); the number converters used is similar when comparing the strategy $minBuff$ to the case of no FDL. When FDLs are introduced however, $minConv$ strategy dramatically minimizes the use of converters.

3.5 Conclusions

In this chapter, contention resolution options were discussed in terms of probing strategies and key design parameters. By utilizing an OPS switch model with a shared converter pool and output FDL buffers, the influence of the number of converters over the loss ratio probability was evaluated first; showing that there is a lower boundary below the maximum number of converters from which packet loss probability would not lessen anymore when adding more converters. It is also shown that both strategies perform better when more fibers per link are disposable. Once FDL buffers are introduced, the probing strategies minConv and minBuff start to perform differently, due to this new degree of freedom. The results demonstrate that the performance can be optimized given a certain resource allocation by using one of those strategies; or that a model may be built for obtaining the most efficient use of its resources according to a predetermined strategy. It is shown that, with enough FDL buffer capability present, minConv achieves lower loss probabilities than minBuff when a small number of converters is utilizable. On the other hand, as the number of disposable converters increases, minBuff achieves lower loss probabilities due to its lower loss probability boundary. Delay induced at the buffers would be other factor to consider; however, as the simulated scenario assumes transparent packet processing, it is insignificant when comparing the buffering delay to the transmission or propagation times.

Chapter 4

Matrix model for calculating and minimizing packet blocking in a single-switch OPS scenario

All-Optical Networks are intended to permit high-speed routing by avoiding the bottleneck of optoelectronic operations. One of the main challenges for a Wavelength Division Multiplexing (WDM) Optical Packet Switching (OPS) architecture is to decide what to do when two or more packets with the same wavelength request the same outlet of the architecture, which is defined as blocking situation. Contention resolution is utilized when, by means of a Fiber Delay Line (FDL) or a Tuneable Wavelength Converter (TWC), competing packets are stored or converted in order to transmit them subsequently. This type of operation may also generate new blocking situations, because packets that pop out from the buffers force upcoming packets to not utilize those output possibilities, and conversions may involve conflicts with upcoming packets in the wavelength to which the packet was converted at the same time. This paper introduces a matrix method that permits to model these blocking situations, and also to avoid some of them in the analyzed OPS architecture.

4.1 Introduction

All-Optical Networks (AON) intend to provide high-speed operation by avoiding optoelectronic conversions, and to reduce the use of transponders and power consumption in the network [31, 8]. Optical Burst Switching (OBS) and Optical Packet Switching (OPS) are considered the most promising paradigms for increasing bandwidth efficiency over Wavelength Division Multiplexing (WDM) networks [38]: Whereas OBS aggregates user data at the edge of the network by grouping it into variable sized bursts [33], OPS attempts to individually process data into fixed size packets [5]. Both architectures face similar challenges, and one of these is related to blocking situations, which occur when two or more competing packets at the input of the architecture request the same output [39]. Several solutions have been proposed to solve these situations; buffering, Multi-Path Routing (MPR) or link dimensioning. The most common implementations on optical switching architectures are based on WDM, where the challenge of contention resolution lies in determining the procedure to assign resources to the packets: how a burst/packet must be converted to other wavelength by means of Tuneable Wavelength Converters (TWCs) or stored by using Fiber Delay Lines (FDLs).

Algorithms have been proposed in the literacy for implementing resources reservation by scheduling departure time for packets utilizing FDLs [40], and matrix models have been utilized over optical switching architectures to analyze the total system crosstalk and loss performance [41] and to develop min/max searches to approach effectively scheduling problems [38]. However, there are no previous studies over a matrix model intended to analyze blocking situations on an OPS architecture. This model is introduced, which permits to count the blocking situations and allows to reserve outputs for packets that do not need to utilize resources to reach the desired output; permitting to achieve a minimization on blocking situations and reducing the utilization of the converters.

Following, a brief glossary of the terms utilized in this chapter: An 'injection' takes place whenever a packet is introduced at an inlet. 'Assignation' refers to the procedure of allocating the upcoming packets to resources or outputs at each new router state. The time that each router state takes (that is; the time required for assignation and to displace the buffers) is referred to as ‘time slot’. The term ‘slot’ makes reference to each place where a packet could be sent in the context of a slot at an FDL or outlet. Each output link, including its whole wavelength bundle, is referred to as ‘outlet’; and ‘output’ refers to each of the wavelength slots contained in an outlet.

4.2 Switch Description

The architecture of the optical switch studied is shown in Fig. 4.1: WDM signals are injected at each input, and the demultiplexer (DMUX) separates the wavelengths $\lambda_1, \ldots, \lambda_{nw}$, in order to treat the packets in a separate manner. Afterwards, packets are processed attempting to avoid dropping in blocking situations by making use of the resources: TWCs and FDLs. The router has the functions of packet dropping (absorption), adding (injection), wavelength switching (conversion), space switching and buffering. When a blocking situation occurs, wavelength conversion, prior to packet buffering, will be the preferred method to solve it such as the $minBuff$ strategy from the previous chapter.

Several parameters are involved in the performance of the different events above depicted:

Architecture: The architecture of all-optical routers is closely related to its physical realization, focusing on the switch complexity, buffer size and number of wavelengths. Different architectures have been discussed for OPS [37]. For analyzing the adequacy of the matrix method, the one of the Fig. 4.1 is utilized.

TWCs: Converters may provide full or partial functioning, depending on its number related to the number of inputs and wavelengths. The role of a converter pool is to share a given number of TWCs among the inputs, thus providing converting capability within a limited conversion

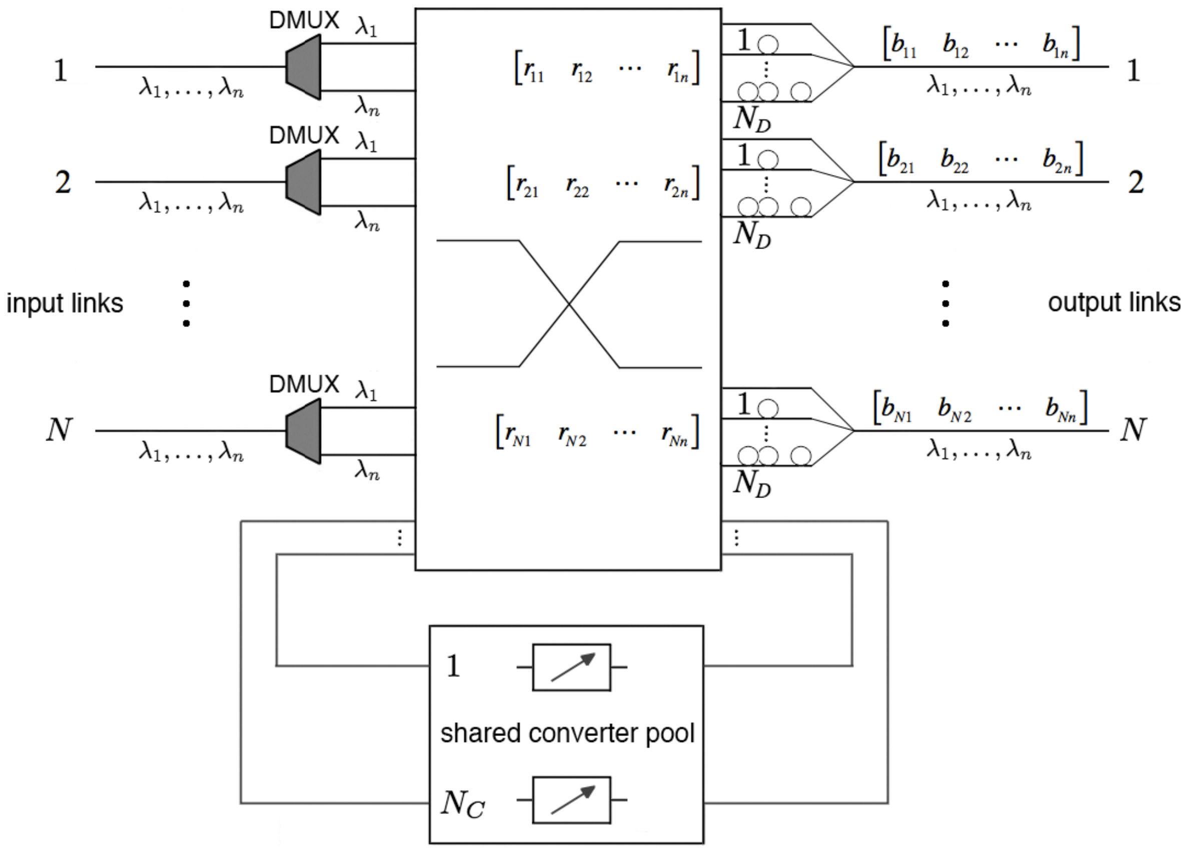


Figure 4.1: Analyzed OPS architecture and definition of vectors.

rate. When a packet is switched to a different wavelength, new blocking situations may surface if upcoming packets in the same time slot request the use of the wavelength to which the packet was converted.

FDL buffers: A different FDL buffer with N_D delay lines is utilized for each outlet, intending to provide buffering to solve blocking situations. Once a packet is stored in the buffers, it will be sent out immediately when it reaches the end at the FDL; this means that no upcoming packets can be injected in that output while in the same time slot. In this manner, buffering of packets may generate blocking situations in the upcoming time slots.

4.3 Design and Implementation

4.3.1 Definition of Modelling Matrices

Different vectors are introduced for each output link of the architecture in order to model the current and the requested occupation of its wavelengths. Its objective is to model the occupation in the most efficient manner and they are processed in form of compounded matrices. Fig. 4.1 shows the vectors in a conceptual maner.

As stated, when a packet occupies a slot in a FDL, it will pop up after a certain number of time slots, depending on the length of the fiber, and it will occupy the correspondent outlet no matter what the requests are. Thereby, buffer occupation in the previous time slots define entirely the actual occupation of the outputs before starting the packets assignation. This information is stored for each outlet i, in the vector B_i as shown in (4.1) and its elements are defined following the guideline of (4.2).

$$B_i = \begin{pmatrix} b_{i1} & b_{i2} & \cdots & b_{in} \end{pmatrix} \tag{4.1}$$

$$b_{ij} = \begin{cases} 0 & \text{if buffer at outlet i is empty on wavelength j} \\ 1 & \text{if buffer at outlet i is not empty on wavelength j} \end{cases} \tag{4.2}$$

Note that no more than one packet can pop out from a buffer at the same wavelength in one time slot. Thereby B_i is always in a binary vector.

Matrix B is formed by the buffer occupation vectors for each outlet; it contains information regarding the wavelength and the outlet for every packet that pops out from a buffer at each time slot.

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{N1} & b_{N2} & \cdots & b_{Nn} \end{pmatrix} \tag{4.3}$$

To characterize completely the system in terms of requests at the outputs, it is necessary to define also the R_i vector for each outlet, which contains information from the wavelength requests of injected packets at the inlets at every time slot:

$$R_i = \begin{pmatrix} r_{i1} & r_{i2} & \cdots & r_{in} \end{pmatrix} \tag{4.4}$$

Each element of Ri is defined depending on the requests over output i with wavelength j as shown in (4.5):

$$r_{ij} = \begin{cases} 0 & \text{if there are no packets requesting the output } i \text{ on wavelength } j \\ k & \text{if there are k packets requesting the output } i \text{ on wavelength } j \end{cases} \tag{4.5}$$

Analogously to the buffers occupation, matrix R defines entirely the packet requests at each time slot for every output:

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{N1} & r_{N2} & \cdots & r_{Nn} \end{pmatrix} \tag{4.6}$$

The introduced matrices are updated at each time slot, and allow to calculate the number of blocking situations given in advance to packet assignation. By means of its use, it is also possible to avoid some blocking situations by means of simple consultations.

4.3.2 Blocking Situations Calculation

To calculate blocking situations, two different stages are differentiated: The first stage refers to the blocking situations prior to the assignation of packets to the outputs, the second one includes also the blocking situations that may surface during packet assignation:

Stage 1: Blocking Situations before starting the Packet Assignation

The number of blocking situations before starting the packet assignation to the outputs is calculated by taking into account two different considerations:

The first one refers to the blocking situations owed to a packet request over an output that is already occupied by another packet popping out from the buffer on the same output. At every time slot, the total of these blocking situations caused by the use of buffers is calculated by (4.7). That is, a blocking situation over an slot that is occupied by the buffer (b_{ij}) is counted per each request (r_{ij}) on that same slot. The second consideration refers to situations where two or more injected packets request an outlet with no packets popping out from the buffer ($b_{ij} = 0$) on the same wavelength: To calculate the total packet blocking situations due to multiple requests over a disposable output, (4.8) is used. Thereby, the total number of blocking situations prior to the packet assignation is given in (4.9).

$$B_b = \sum_{i=1}^{N} \sum_{j=1}^{n} b_{ij} \cdot r_{ij} \tag{4.7}$$

$$B_r = \sum_{i=1}^{N} \sum_{j=1}^{n} (r_{ij} - 1) \text{ when } r_{ij} \geq 2 \text{ and } b_{ij} = 0 \tag{4.8}$$

$$B_T = B_b + B_r \tag{4.9}$$

Above defined blocking situations owe entirely to the arrangement of packets popping out from the buffers (Information contained in B matrix) and to the outputs requested by upcoming packets (Information contained in R matrix).

Stage 2: Blocking Situations given during the Packet Assignation

An additional consideration concerning blocking situations takes place when the switches' procedures determine in a random sequence which injected packet would be the next one to process. In this case, there may be packets assigned to disposable outputs by means of conversion that overlap with requests from packets that have not been assigned yet. These cases induce additional blocking situations to the previously calculated ones.

In order to compute these cases with the defined procedure, modifications over R matrix (4.10) are required during packet assignation: by summing 1 to the correspondent r_{ij} (output i over the wavelength j) when a conversion and immediate injection takes place in that output as shown in (4.11), these additional blocking situations are accounted and ready to process by the above depicted method.

$$R' = \begin{pmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{N1} & r'_{N2} & \cdots & r'_{Nn} \end{pmatrix} \tag{4.10}$$

$$r'_{ij} = \begin{cases} r_{ij} + 1 & \text{if a packet was assigned to the output } i \text{ on wavelength } j \\ r_{ij} & \text{otherwise} \end{cases} \tag{4.11}$$

Note that only a unit can be summed to r_{ij}, since no more than one packet can be assigned to an output during a single time slot. Once this R' matrix is entirely defined (i.e: once all the packet assignations are also processed), it is possible to calculate the new number of blocking situations by means of (4.7), (4.8) and (4.9), utilizing r'_{ij} instead of r_{ij}.

4.3.3 Blocking Minimization Strategy

As shown in the previous subsection, there are three different cases compounding two stages that may induce blocking situations in the operating. Blocking situations in the first stage refer to the utilization of the buffers in previous time slots combined with the configuration of upcoming packets, and to the arrangement of the upcoming packets by itself; Blocking situations in the second stage are given by the procedure utilized for assigning packets to the outlets. The strategy for minimizing blocking situations focuses on the second stage: As explained, the processing of packets may generate blocking situations over packets that have not been processed yet; these cases are find to be completely avoidable.

This fact is illustrated by the following example: The architecture shown at Fig. 4.1 is utilized, with $N = 4$ outlets, $n = 4$ wavelengths, full converters range $N_C = 16$ converters (4 wavelengths $\cdot$ 4 inputs) and $N_D = 4$ FDLs. Equations (4.12) and (4.13) are introduced to define the occupation and requests at outlet 1 in a certain time slot:

$$B_1 = \begin{pmatrix} b_{11} & b_{12} & b_{13} & b_{14} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix} \tag{4.12}$$

$$R_1 = \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 & 0 \end{pmatrix} \tag{4.13}$$

From (4.12), find that the 1^{st} wavelength is not utilizable at outlet 1 because there is a packet popping out from the buffer ($b_{11} = 1$). Since the first packet to assign to the outlets is determined in a random manner, considering (4.13) it is possible to this packet to be the one requesting that same slot; r_{11}, resulting in a blocking situation. Thereby, without considering the rest of requests; since $b_{13} = 0$, it is also possible to this packet to be assigned to the $3rd$ wavelength on this output, inducing a new blocking situation to the packet requesting that slot ($r_{13} = 1$), which will now require an extra conversion to assign it to the other disposable wavelengths ($b_{12} = 0$ and $b_{14} = 0$). However, this additional blocking situation could have been avoided by assigning the packet coming in the 1^{st} wavelength to any of the other disposable wavelengths (b_{12} or b_{14}). There could be situations when more requests are found, in which this need for an additional conversion could induce new blocking situations to the rest of requesting packets on the outlet.

The blocking minimization strategy is implemented by forcing packets in blocking situations to not utilize wavelengths that other packets can use without conversion. In this way, there is no longer need to modify the R matrix, and blocking situations are minimized to the ones of the first stage.

4.3.4 Model for Performance Evaluation

A simulation tool in C++ modeling the architecture is used, simulations run for 10^6 clock cycles over an OPS synchronous switch model. Injected packets are uniformly distributed over the outlets and wavelengths. The node has N input and output links with one fiber per link, and n wavelength channels per fiber. The number of converters in the pool is given by N_C, and is always set to the maximum ($N \cdot n$). Each outlet has an FDL buffer with N_D fiber-delay lines. There are two architectures analyzed; the first one corresponds to a 4×4 switch architecture (4×4 model) that has $N = 4$ outlets, $n = 4$ wavelengths, $N_D = 4$ FDLs and $N_C = 16$ converters; the second one corresponds to an 8×8 switch architecture (8×8 model) that has $N = 8$ outlets, $n = 8$ wavelengths, $N_D = 4$ FDLs and $N_C = 64$ converters.

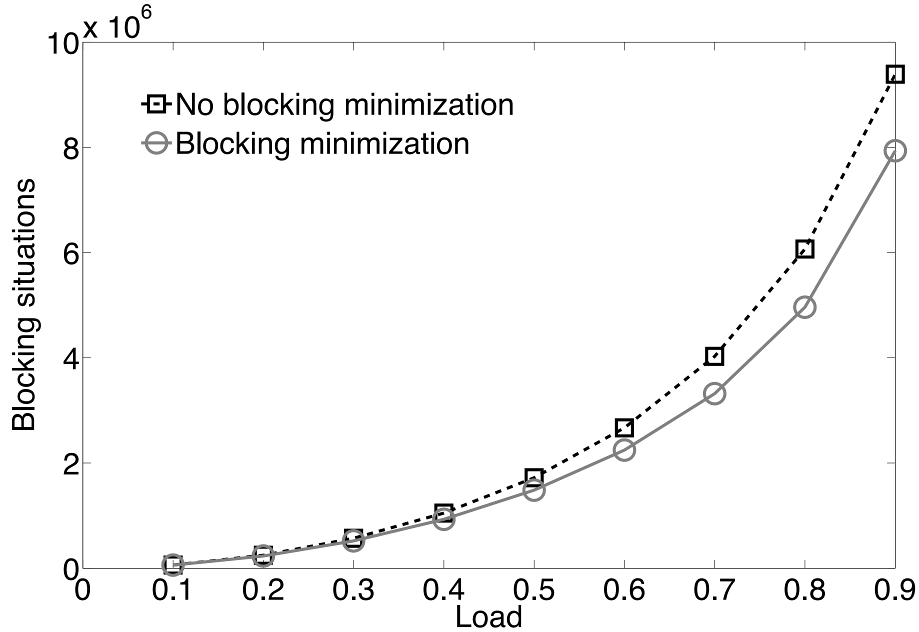
The number of blocking situations and its implications over the utilization of converters for both implementation and no implementation of blocking minimization strategy were analyzed.

4.4 Performance Evaluation and Results

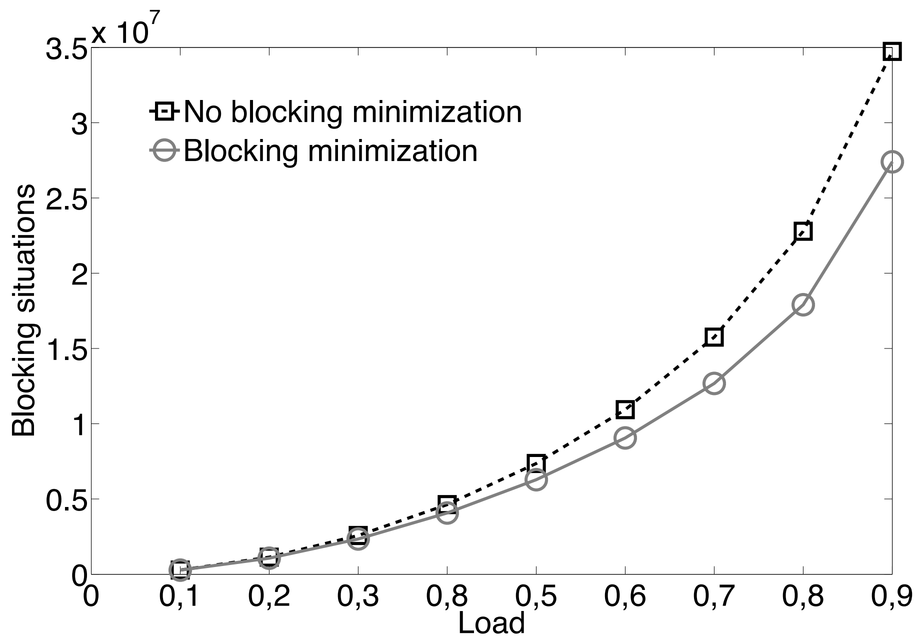
4.4.1 Number of Blocking Situations

Number of blocking situations vs. load for the 4×4 model is represented in Fig. 4.2(a) by utilizing both; blocking and no blocking minimization. The avoided blocking situations are determined by the difference between the plotted values for each load value. Those become more appreciable as the load value is increased, achieving earnings of more than 10^6 blocking situations for load values of 0.8 and 0.9.

As observed in Fig. 4.2(b), more blocking situations can be avoided for the 8×8 model with the same load values, reaching values higher than $7 \cdot 10^6$ for a 0.9 load value. This is due to the greater freedom when converting packet channels, since a larger wavelength bundle is available.



(a)



(b)

Figure 4.2: (a) Number of blocking situations vs. load. $N = n = 4$. (b) Number of blocking situations vs. load. $N = n = 8$.

4.4.2 Converters Utilization

The following results illustrate the utilization of converters for the two models analyzed.

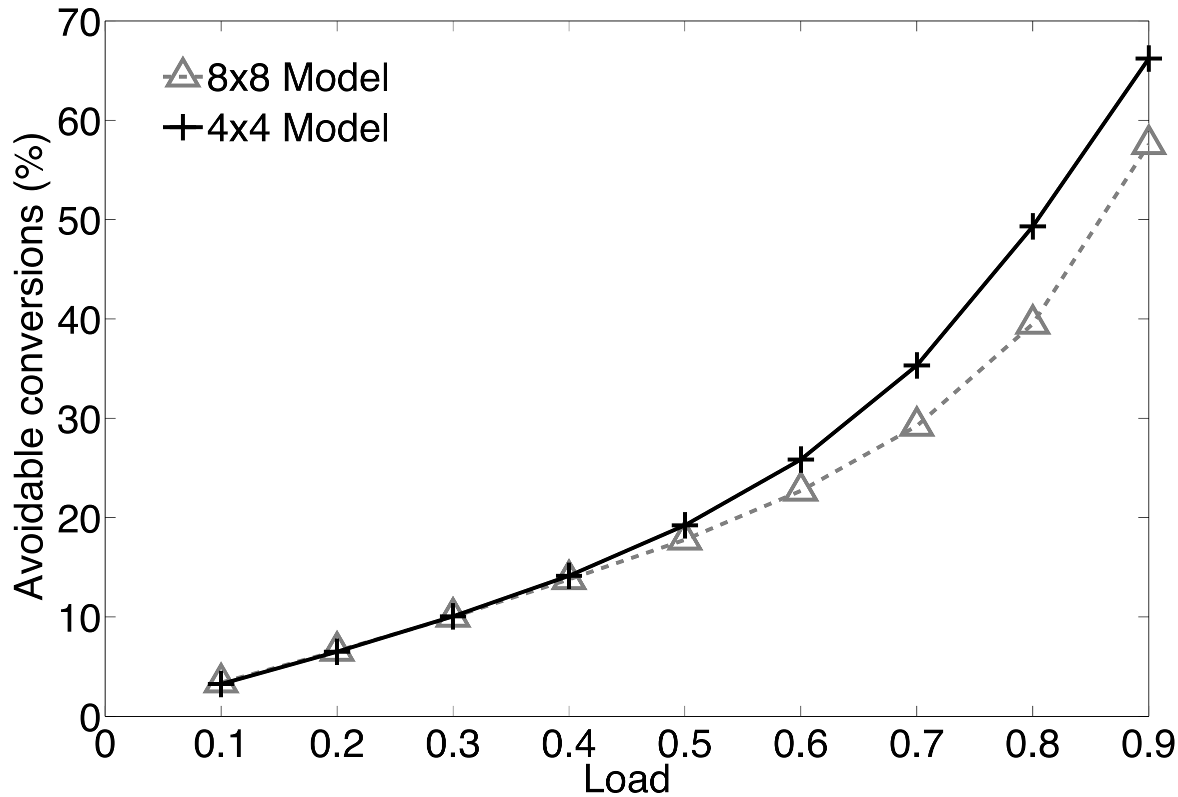
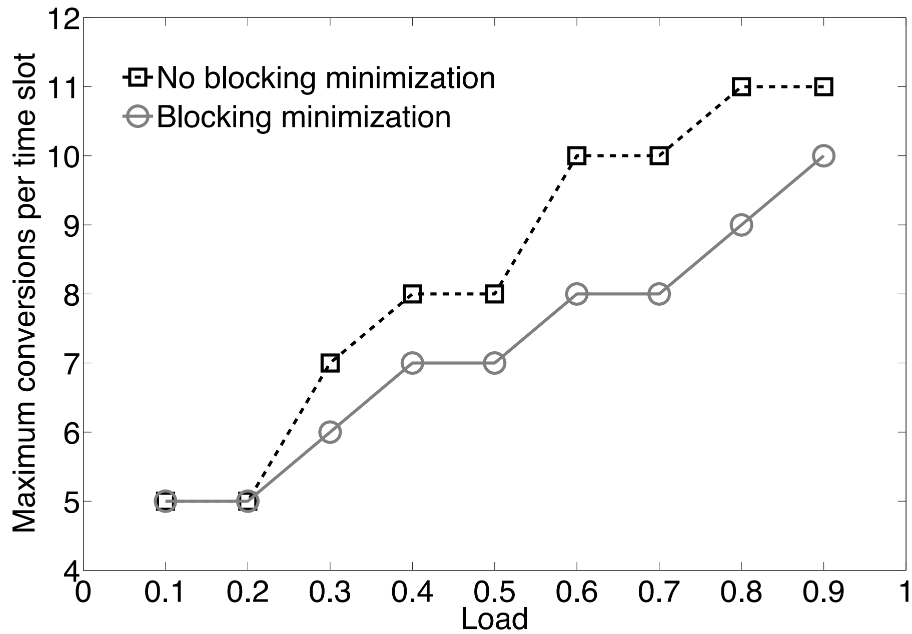
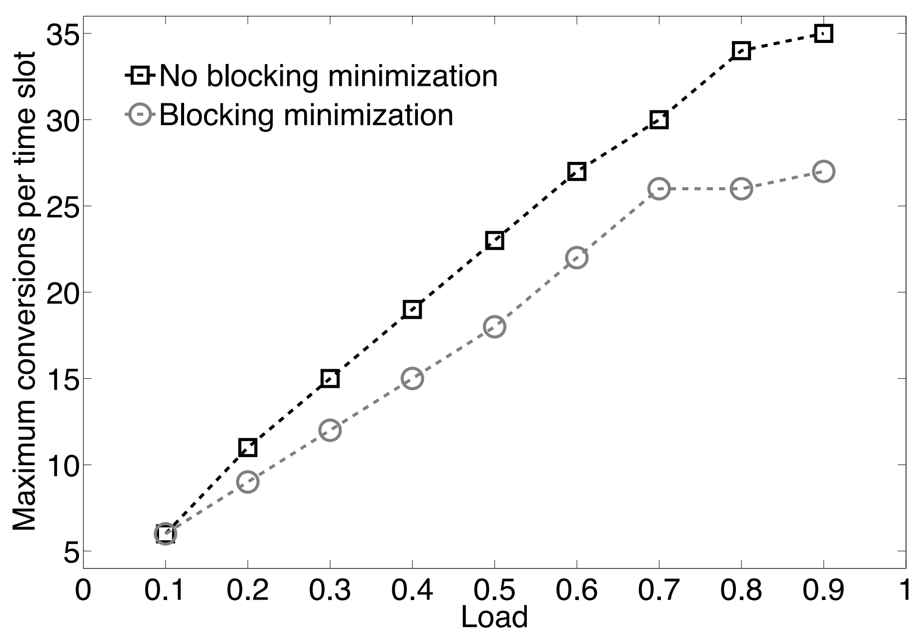


Figure 4.3: Percentage of avoidable conversions.

The percentage of additional conversions that take place when no strategy is implemented when compared to the case of blocking minimization strategy is shown at Fig. 4.3 for both 4×4 and 8×8 models. As load increases, more conversions become avoidable by implementing the blocking minimization strategy. The pattern is similar for both models, permitting to avoid more than 60% of the total conversions for the 4×4 model, and more than 50% for the 8×8 model at 0.9 load. The difference between models is due to the cumulative higher probability of choosing a wavelength that is already occupied in the 8×8 model when compared to the 4×4 model for the same load values.



(a)



(b)

Figure 4.4: (a) Maximum conversions per time slot vs. load. $N = n = 4$. (b) Maximum conversions per time slot vs. load. $N = n = 8$

The impact of the strategy on the total number of converters needed to solve all the blocking situations with the utilized parameters is depicted at Fig. 4.4. The maximum number of conversions that took place during one time slot for the whole simulation time is represented vs. the load. Fig. 4.4(a) represents the 4×4 model. Once again the differences start to become apparent for higher load values, since low load values do not imply many additional conversions. It is shown that 1 or 2 converters could be saved for load values higher than 0.3, since no packets would utilize them when implementing the blocking minimization strategy.
On the other hand, the 8×8 model permits higher converter saving, in Fig. 4.4(b) it is shown that up to 8 converters can be saved for the cases of 0.8 and 0.9 load value; which means that about an additional 30% of the total of converters would be needed to operate without the blocking minimization strategy in the same conditions.
The utilization of the blocking minimization strategy had no effects in the overall packet-dropping rate. This is due to the full conversion capability of the scenario, since the strategy implementation is only incumbent to the packet assignations to the converters, and there are enough to convert all the upcoming packets at every time slot.

4.5 Conclusions

In this chapter, a matrix model for analyzing blocking situations over an OPS architecture was introduced. By means of its analysis it was shown that it is possible to develop an strategy to minimize the blocking situations by simple matrix consultations. By utilizing an OPS switch model with output FDL buffers and full conversion capability, the influence of this strategy over the number of blocking situations was evaluated first; showing that some of the blocking situations could be avoided by considering prior to assignation what the packet requests are for each outlet. Blocking minimization strategy was also analyzed in terms of converters utilization. The results demonstrate that the utilization of converters could be slightly minimized.

Chapter 5

Conclusions and future work

5.1 General conclusions

An extensive study into the performance features of different OPS architectures and networks was performed. Different strategies were developed in an analytical framework, allowing comparisons between those. Following, an analysis on the results is detailed for the problem statement framework provided in the first chapter:

Resource allocation. Resource allocation is the main topic of study of the first chapter, where different routing strategies are analyzed in terms of their needs of fibers and delay lines for optimal functioning. It is shown that MPR offers substantial saving in the number of fibers required by the network when compared to WP routing methods. In the third chapter, resource allocation is found to be closely related to the contention resolution strategy choice. Architectures can be build according to a predetermined strategy attempting to optimize its performance in terms of packet loss probability.

Blocking situations. Blocking situations are analyzed along with the matrix method in the fourth chapter. Matrix method solves to define each type of blocking situation and is utilized to eliminate the avoidable ones, resulting in a more efficient utilization of converters.

Packet dropping. Packet dropping is analyzed in the third chapter. It is shown that there is a lower boundary in the number of converters deployed from which the packet dropping rate would not improve anymore by adding more converters. Afterwards, packet dropping probability is used to differentiate the performance of the defined strategies, showing that given a certain architecture, packet dropping rate may be optimized depending on the priority given to the use of its resources.

Computing complexity. Computing complexity was not evaluated in quantitative terms. The matrix model of the fourth chapter minimizes blocking situations, thus implies less operations improving the efficiency of the system in this ambit.

5.2 Future Work

Further research on the introduced topics is to be done. Future work must consider:

Link failures in network scenarios. Additional network simulations are required to quantify the full potential of MPR, since its capability of responding to multiple simultaneous link failures has not been fully studied.

Strategies. Defined strategies should be applied to network scenarios, intending to save resources by introducing asymmetric buffering capacity to solve contention resolution, getting advantage of the nonuniform network traffic.

Matrix model. The matrix model defined is still in an early stage of development. The introduction of the matrix method in the whole switch operating, intending to implement procedures that could fully determine how to assign each packet by matrices utilization represents a promising topic of study.

Computing complexity. Parallel computing strategies possibilities should be studied along with the matrix model, attempting to obtain a more efficient system regarding packets assignation.

Optical Burst Switching. The analytical methods proposed are suitable to be applied to OBS architectures, to quantify the full potential for each architecture and establish a coherent comparison with the described strategies.

Appendix A

List of Acronyms

AON	All-Optical Networks
C++	Programming language utilized
DMUX	Demultiplexer
FDL	Fiber Delay Line
IP	Internet Protocol
LNH	Least Number of Hops
minBuff	Minimum packet buffering strategy
minConv	Minimum conversions strategy
MPR	Multi-Path Routing
NGI	Next Generation Internet
OBS	Optical Burst Switching
OLS	Optical Label Switching
OPS	Optical Packet Switching
SD	Shortest Distance
SPR	Single Path Routing
TOPS	Transparent Optical Packet Switching
TWC	Tuneable Wavelength Converter
WDM	Wavelength-Division Multiplexing
WP	Working-Protection paths
WP-LNH	Working-Protection paths with Least Number of Hops
WP-SD	Working-Protection paths with shortest distance

Table A.1: List of Acronyms

Appendix B

List of Symbols

λ_i	Wavelength number i
b_{ij}	Buffer state element for outlet i and wavelength j
B	Matrix for buffers state
B_b	Blocking situations due to buffers state
B_i	Buffers state vector for outlet i
B_r	Blocking situations due to requests
B_T	Total blocking situations
N_F	Number of fibers per link
n	Number of wavelength channels
N	Number of inputs and outputs
N_C	Number of shared converters
N_D	Number of delay lines
r_c	Conversion ratio
R	Matrix for requests
R'	Modified matrix for requests
R_i	Requests vector for outlet i
r_{ij}	Request element for outlet i and wavelength j

Table B.1: List of Symbols

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